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REVIEW

Microplastics flow in the food chain through agricultural practices: *quo vadis*

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Abstract

The plastic particles with a diameter of less than 5 mm are called microplastics (MPs) and have become persistent contaminants of the environment with important implications for agricultural systems and food safety. This review aims to integrate the current understanding of sources, transport, and effects of MPs in agricultural landscapes, with a particular focus on their subsequent transport within the food web chain. MPs in agricultural soils may enter through various routes, such as the application of sewage sludge, degradation of plastic mulch films, irrigation with contaminated water, and atmospheric deposition. Once introduced, they enter the food chain under the influence of soil properties, microbial communities, and plant systems, impacting soil fertility and nutrient cycling. Transport of MPs from soil to root, followed by uptake and translocation to edible organs, is a food safety and human health issue. MPs also serve as vectors of agrochemicals, heavy metals, and pathogens, increasing their ecotoxicological and toxicological risks. MPs also affect soil structure, decrease microbial diversity, and impact yields. Therefore, this review highlights essential knowledge gaps regarding the long-term persistence of MPs in soils, bioavailability, and impact, which could be cumulative along the trophic chain. For this, regulation systems, agricultural practices, and detection and mitigation strategies, qualitative and quantitative, for MPs should be devised.

Keywords: plastic pollution; health risk; *quo vadis*; environmental pollution

1. Introduction

Microplastics (MPs) are plastic particles smaller than 5 mm in size that originate either from waste plastic or directly manufactured as microbeads and fibers, etc (An et al., 2020). Because of their persistence, widespread distribution, and potential to be toxic, MPs have come to be regarded as a major environmental contaminant with implications on ecosystems and human well-being. Whereas MPs in marine ecosystems have been much studied, MPs in terrestrial ecosystems, especially agro landscapes, have been studied in the scientific literature just recently (Lwanga et al., 2022). Agriculture is a key sector where MPs tend to accumulate in soil, water, and biota, and could thus affect food safety and food production (Jin et al., 2022). MPs have the potential to absorb and carry varied agrochemicals, pathogens, as well as heavy metals, and hence their implications on the environment and on humans increase manifold (Perković et al., 2022). It is therefore important to research their sources, pathways, and potential implications along the food chain in order to evaluate long-term sustainability and develop mitigation measures (Lehel & Murphy, 2021).

MPs in agricultural systems originate from a variety of sources, ranging from fertilization with sewage sludge, plastic mulch, irrigation with MP-contaminated water, and atmospheric deposition (Uwamungu et al., 2022). Sewage sludge applied as a soil fertilizer is rich in organic matter and nutrients and is one of the key channels through which MPs transport synthetic particles and fibers that get accumulated in the soil over time (Cydzik-Kwiatkowska et al., 2022). Plastic films applied as plastic mulch, which is usually applied to retain water, prevent weed growth, and regulate soil temperature, also break down over time and release MPs into the environment. Others involve agricultural plastic items such as those of greenhouse films, drip irrigation systems, and polymer-coated fertilizers that break up with weather mechanical forces, and microbiological processes (Cusworth, 2023). Urban and industrial runoff, atmospheric transport from regions with high plastic use, and tire wear particles further drive the introduction of MPs into agricultural landscapes. Soil properties, microbial degradation, and root interactions affect the fate of MPs in these systems and prompt questions about the persistence and transfer of MPs along the food chain (Okeke et al., 2022).

Such MPs affect food safety and soil health, along with wider ecological functions. MPs have been found in edible parts of plants, which are, therefore, directly consumed by consumers (Oleksiuk et al., 2022). MPs have been said to be taken up by plant roots and be translocable to aerial tissues, but further study is needed to know the fate and impact of MPs in plants on the well-being of humans (Aransiola et al., 2023). MPs can also be vectors of persistent organic pollutants (POPs), pesticides, and heavy metals, increasing the toxicological burden of contaminated food products. Their effect on soil health is also of equal importance since MPs have the potential to change soil structure, biochemical processes, and nutrient cycling, with further consequences on agricultural productivity and ecosystem services (F. Wang et al., 2022). We are, however, still hampered by the insufficient knowledge on the potential effect of MPs, particularly on the agricultural soil ecosystem, and the long-term food safety and sustainability threats (Briassoulis, 2023). It is, therefore, important to have a thorough knowledge of MP dynamics in agricultural ecosystems to inform the design of effective policies and mitigation strategies.

Therefore, the aim of this review was to synthesize the current state of knowledge regarding sources, transport, and impacts of MPs in agroecosystems, including within the food chain. The review aims to give an overview of how MPs are exchanged and proceed onward in soil-plant systems, their interaction with agrochemicals, and their eventual risks to human and environmental health. The big question — *quo vadis* (where are we heading?) — focuses on the surging need to quantify what future trajectories might look like across research, policy, and management to minimize MP contamination of agricultural landscapes.

2. Sources of microplastics in agriculture

The abundant application of plastic materials during modern agriculture has led to the accumulation of MPs in soil, water, and crop systems (Azeem et al., 2021). From both the primary (direct addition of plastic) and the secondary (where larger plastic materials were broken down over time) sources, MPs enter agricultural landscapes. Therefore, the presence of MPs in soil and their potential transfer through the soil into food chains raises questions about food safety and the sustainability of the environment (Mamun et al., 2023). Agricultural MPs come primarily from plastic mulches, biosolids and compost applications, irrigation activities, and agrochemical packaging. The contribution of these sources to MP pollution depends on plastic types, environmental conditions, and agricultural land management (Khalid et al., 2023).

2.1. Plastic mulches and films

Because it improves crop yields by retaining soil moisture, keeping out weeds, and controlling soil temperature, plastic mulches, and films are widely used in agriculture (Abbate et al., 2023). These materials, usually produced from polyethylene (PE), are applied on top of the soil and remain throughout the season. Nonetheless, poor disposal, mechanical stress, and exposure to the environment make them degraded, which results in the release of MPs (Liu et al., 2022). After a while, microbials, UV rays, and temperature variations split plastic mulches into smaller and smaller pieces of micro- and nanoplastics, both of which work their way into the soil matrix. Plastic mulches are widely used, leading to increased MP contamination of agricultural soils, especially in intensive farming systems (Feng et al., 2021). Scientific studies have found that MP concentrations were higher in fields of long-term plastic mulch than in similar fields without plastic coverings (van Schothorst, 2021). These MPs show a high persistence in soil, which raises questions regarding soil biota, changes in physicochemical properties, and potential plant uptake. Biodegradable plastic mulches have been developed to replace conventional ones; however little is known about their degradability in the field, and partial degradation may still contribute to MP pollution (Qi et al., 2020). This emphasizes the importance of sustainable mulch disposal strategies and alternatives to plastic mulch that can minimize the release of MPs into the environment for mitigating the long-term implications of plastic-based mulching.

2.2. Biosolids and compost applications

Biosolids and compost are discarded organic waste materials that are often employed on agricultural soils to improve soil fertility and soil organic matter (Radford et al., 2022). Biosolids, which are the byproducts of treated sewage sludge, are nutrient-rich, but they also contain numerous contaminants, including MPs (Prus & Wilk, 2024). These MPs come from household wastewater, industrial effluents, and textile fibers that survive wastewater treatment processes. A huge percentage of major MPs end up in sludge, which is dumped on agricultural fields as fertilizer despite treatment (Corradini et al., 2019). MP pollution of biosolid-amended soils has been widely documented and this pollution has been described at least in treated fields as synthetic fibers and microbeads. The retention of MPs in the soil is affected by particle size and density as well as other physical and chemical features of the soil. Wind or surface runoff might carry lighter MPs while heavier particles are more likely to get embedded in soil agglomerates (Barman et al., 2024). MPs in biosolids can also affect soil microbiomes, which will influence nutrient cycling and soil fertility. Manure or compost, processed organic waste, is another source for MPs in agricultural soils. Plastics that are not sorted properly contaminate the final output by breaking it down into smaller pieces during composting processes. MPs have been identified in compost made from municipal waste, food scraps, and garden trimmings and this has been shown to remain after land application (Porterfield et al., 2023). MPs in non-reproductive tissues bring into question the potential influence of MPs on soil health, plant uptake, and trophic transfer in food webs (Rose et al., 2023). Continued work on refining waste management practices, developing better composting protocols, and setting limits on plastic pollution of biosolids and compost will be necessary to reduce MP input into agricultural soils.

2.3. Irrigation practices

Water used in irrigation can be the pathway of MP contamination in agricultural regions. MPs have been found in freshwater sources such as rivers, lakes, and reservoirs, that feed irrigation systems (Bexeitova et al., 2024). Most of the MPs recovered in irrigation water is attributed to urban runoff, industrial effluent, and atmospheric deposition. MP contamination is much more likely, however, where treated or untreated wastewater is applied to irrigation (Picó et al., 2020). Flood irrigation, sprinkler systems, and drip irrigation can distribute MPs into plant and soil systems. MPs in irrigation water have been shown by other studies to penetrate the soil profile, impacting soil structure, water holding, and microbial interaction (Xing et al., 2025). Additionally, since MPs in irrigation systems get entrapped in pipes and nozzles, MPs impact water flow and efficiency (Ra, 2022). Little is known about the fate of MPs initially introduced through irrigation, however, the specific interaction of MPs with soil colloids, organic matter, and root morphology is an active area of research (Azeem et al., 2021). Filtration systems, drinking water quality monitoring, and prohibition of wastewater irrigation in sensitive agricultural zones are some potential measures to reduce MP contamination from irrigation sources (Briassoulis, 2023).

2.4. Agrochemical packaging and littering

Agrochemicals, such as fertilizers, pesticides, and herbicides, are commonly used, resulting in increased plastic packaging and augmented dispersion without proper disposal, leading to MP pollution (Bashir et al., 2020). Agrochemicals are often stored in plastic containers, which can degrade over time from exposure to the environment. Residual plastics from containers, plastic-coated fertilizers, and pesticide-treated seeds lead to the entry of MPs into the soil (Sa'adu & Farsang, 2023). Inappropriate disposal (open burning; abandonment of plastic waste in fields) further compounds MP contamination of agricultural landscapes.

Another potential source of MPs is fertilizers coated with synthetic polymers for slow nutrient release (Bhattacharjee et al., 2025). These coatings do improve nutrient efficiency but degrade over time, ultimately suspending polymer residues in soil. The same is true for pesticide formulations that employ polymeric carriers or encapsulated active constituents that add to MP accumulation (Machado et al., 2022). These materials disintegrate under field conditions (high temperature, moisture, sunlight, etc.) into the release of MPs that remain in the soil and can be absorbed by plants (Zhao & Zhang, 2023). Littering (of agricultural plastics, such as greenhouse films, irrigation tubes, and plastic seedling trays) contributes to MP pollution (Briassoulis, 2023). Plastics not recycled or poorly disposed of accumulate on farmland, where i.e. mechanical and environmental forces break pieces down into MPs (Lwanga et al., 2022). To mitigate the problem, better agricultural plastic waste management practices, wider adoption of biodegradable packages, and regulations on agrochemical container disposal could be implemented.

3. Transport and fate of microplastics in agroecosystems

MPs in agroecosystems show complex translocation and transformation processes that depend on environmental parameters, agricultural practices, and physicochemical interactions with soil, water, and biota (Yadav et al., 2022). MPs are persistent in multiple environmental compartments (and within soil systems), being degraded and accumulated, exhibiting movement across different trophic levels (i.e., after becoming introduced into agricultural fields via plastic mulches, biosolids, irrigation water, or agrochemical packaging). Thus, it is crucial to develop an understanding of the transport and fates of MPs in agroecosystems to assess their potential effects on soil health, crop productivity, and food safety (Sharma et al., 2023). The main processes controlling MP behavior are their persistence in soil, their uptake by plants, and their transport through water systems, by runoff and leaching.

3.1. Soil dynamics

Soil is the major sink accumulation of MPs in agroecosystems, and persistence is governed by the type of polymer, environmental conditions, and physicochemical properties of the soil (Rehm et al., 2021). Environmental and microbial degradation resistance of MPs might allow them to persist in the soil matrix over long periods. While some MPs gradually break down by photolysis, oxidation, and microbial degradation, MP degradation to smaller particles called nanoplastics might increase their persistence and potential bioavailability in the environment (Alimi et al., 2018). MP degradation in the soil is polymer-type specific: Polyethylene (PE) and polypropylene (PP) undergo different decomposition processes and lifetimes than polystyrene (PS) (Ainali et al., 2021). Fragmentation and mineralization of MPs depend on temperature, moisture content in the soil, and microbial populations. Because many synthetic polymers have low biodegradability, MPs might also persist and build up in soils over time and cause long-term pollution (Yuan et al., 2020). MPs interact with soil particles, organic matter, and microbial populations in soil and affect soil properties and ecological processes. Experiments indicate that soil structure changes caused by MPs affect soil porosity, water holding capacity, and nutrient dynamics (F. Wang et al., 2022). MPs have also been reported to adsorb and co-migrate with persistent organic pollutants (POPs), heavy metals, and agrochemicals, which might change their bioavailability and toxicity relative to soil environments (Okoye et al., 2022). Such processes might have cascading effects on microbial diversity and soil fertility, ultimately affecting crop productivity, and hence, further research is required to explore the long-term effect of MP buildup in agricultural soils.

3.2. Plant uptake

Evidence indicates that MPs could be ingested by plants, which could lead MPs to enter the food chain (Cverenkárová et al., 2021). Larger MP particles stayed within soil systems, while smaller ones and nano-plastics penetrated root systems via fissures, root hair, or endocytosis (Nigina et al., 2024). Therefore, particle size, surface charge, and root exudate interaction could influence MPs' uptake by plants, promoting their absorption and transportation within (Xu et al., 2022). Experiments conducted using hydroponic systems and matured soil systems confirmed MPs' translocation in roots to aerial parts of the plant, i.e., stems, leaves, and edible parts of the plant (Lima et al., 2023). Such findings indicate that MPs could penetrate the vascular systems of the plant, particularly its apoplastic and symplastic pathways (Rong et al., 2024). Crops like lettuce, wheat, and carrots have been reported to uptake MPs, raising concerns about human exposure through food. The detection of MPs in plant tissues could also have physiological and biochemical implications. The plant is damaged through oxidative stress, nutrient uptake, and root structure, affecting plant growth and productivity (Colzi et al., 2022). Additionally, co-contaminants like pesticides and heavy metals could interact with MPs to increase toxic effects, complicating risk assessment (Bhagat et al., 2021). Considering the lack of data, so far, regarding the contamination of edible crops with important human markers of contamination and the risk associated with chronic exposure via resources, more studies are anticipated to assess the threat posed by edible plants manipulated by MPs (Nelis et al., 2023).

3.3. Water systems

Water is a major carrier through which MPs are transported in agroecosystems via surface runoff, leaching, and infiltration into the groundwater (Uwamungu et al., 2022). The mobility of MPs in aquatic environments may be affected by precipitation events, irrigation practices, and runoff, which results in their spread from

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agricultural soils to aquatic environments. Based on the size, density (specific weight), and hydrophobicity MPs are introduced through erosion, through attachment to soil particles, or, for some, in dissolved state (suspension) in water (X. Wang et al., 2021). On the other hand, surface runoff contributes significantly to the lateral transport of MPs, especially in areas with intensive irrigation or heavy precipitation (Ling et al., 2023). MPs in topsoil, or MPs applied to land via biosolids and compost, can be washed into neighboring water bodies and add to the contamination of rivers, lakes, and reservoirs (Naderi Beni et al., 2023). Distance traveled by the MP in runoff depends on soil texture, vegetation cover , and slope gradient and indicates that coarse (larger) particles have a greater tendency for transport than fine particles (Han et al., 2022).

Leaching is another pathway MPs can move and involves the downward movement of MPs into deeper soil layers and possibly even groundwater. Low-density MPs: e.g. polyethylene and polypropylene will exhibit little infiltration while higher-density particles may percolate through soil pores (Gao et al., 2021). Soil moisture can influence whether MPs migrate in soils, and MPs are shown to be able to move in soil profiles under appropriate conditions, particularly in sandy or well-drained soils (Carbery et al., 2018). This puts groundwater at risk of contamination because MPs and related pollutants could contaminate subsurface water sources used for drinking and irrigation (Viaroli et al., 2022). Moreover, MPs in agricultural water systems may deposit in irrigation infrastructure, such as pipes, filters, and nozzles, reducing the efficiency of water distribution. Because they originate from plastic and solid wastes, MPs found in irrigation water, particularly, contribute to persistent contamination of agricultural soils which creates a vicious cycle in which contamination, and therefore, accumulation of MPs in soil continues (Mohajerani & Karabatak, 2020). However, solutions for these problems involve better water filtration systems, tighter regulations for wastewater treatment, and monitoring programs to determine the presence of the MPs in agricultural water sources.

4. Impact on the food chain

MP contamination of agricultural systems poses a serious threat to food safety and ecosystem health (Mamun et al., 2023). Once MPs are found in soil and water aggregate, they enter the food chain through bioaccumulation (i.e., accumulating in plant biomass), and biotransformation through soil microbes as well as transfer to livestock of both terrestrial and aquatic nature (Kumar et al., 2022). The occurrence of MP in edible crops, their impact on soil health and crop production, and the transfer through the food web increase the risk of human exposure and long-term environmental impacts (He et al., 2021). After studying these pathways, strategies may be developed to minimize MP contamination of food production systems.

4.1. Contamination in crops

Emerging evidence shows that MPs end up getting taken up by plants, contaminating the crops we eat. Research has shown that MPs, particularly in the nano-size category, can infiltrate plant root systems through cracks, root hairs, and the endocytosis process (Gümüş et al., 2023). Once they enter, they can translocate themselves to various plant components, such as their stems, leaves, or fruits as a direct entrance to humans (Azeem et al., 2021). MPs were detected in the edible parts of crops including lettuce, wheat, carrots, and rice. Significant evidence in controlled lab settings and field experiments has already established the capability and proof of uptake of MPs in the soil as well as in irrigation water by plants, along with the hoops of their accumulation within plant cells (Carrasco Silva et al., 2021). The ubiquitous presence of MPs in staple crops raises concerns regarding their abundance in the human diet, with potential implications for food safety.

In addition to direct uptake, MPs may also attach to the surfaces of plants, especially for leaf vegetables and root crops, via electrostatic interactions or through soil particles to which MPs can bind (Azeem et al., 2021). Especially when there is a lack of proper washing, the impact of surface contamination and the potential for MP ingestion also increases. Mercury and other heavy metals have been coated onto MPs that attach to contaminated crops, possibly increasing the toxicity of affected crops (Okla et al., 2024). The significant health hazards of co-contaminants in food products (in addition to MPs) support the need for monitoring and regulatory frameworks to ensure that agricultural produce continues to be safe for consumption.

4.2. Effects on soil microbiome and crop productivity

MPs have a significant impact when entering agricultural soils, affecting many parameters from soil microbial diversity to its fertility, nutrient cycling, and plant health. MPs can change microbial diversity and abundance, potentially disrupting important microbial activities that are essential for sustainable agriculture (Jain et al., 2023).

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Research indicates that MPs can induce physical and chemical alterations to soil that impact the habitat structure of microbial communities. Metal-based proteins nm surface hydrophobicity coating can be potential foci of microbial biofilm formation thereby affecting microbial colonization of breast milk (Hale et al., 2020). Although some microorganisms can use MPs as the carbon source through metabolization, the anti-active effects of MPs accumulation on soil microbial networks generally predominate. MPs are known to lower microbial communities that are helpful to plants, like nitrogen-fixing bacteria and mycorrhizal fungi, which can result in reduced soil quality (Aralappanavar et al., 2024).

MPs can act as vectors of pathogenic microorganisms, promoting the transmission of pathogenic bacteria and viruses in soil agricultural soil. Antibiotic-resistant genes have also been identified in some MP particles, which raises questions about the contribution of MP to the dissemination of antimicrobial-resistant bacteria to soil ecosystems (X. Zhang et al., 2024). The interaction between MPs and agrochemicals adds to the challenge: Adsorption of pesticides and fertilizers to MPs alters the bioavailability and persistence of these compounds in soil. Apart from microbial interaction, MPs also alter the physical structure of the soil and the behavior of water, thereby influencing aeration, water holding, and root penetration (Khalid et al., 2020). Such physical structure modifications to the soil make it hard for roots to penetrate and decrease nutrient uptake and, in the long term, yields. Experiments have proved that polluted soils have been accountable for low seed germination rates, poor plant growth, as well as physiological stress on crops (W. Zhou et al., 2023). Soil health is essential to food security on a worldwide level, so MP contamination in agricultural soils is one of the most important emergent issues to be tackled to ensure food productivity sustainability in the future.

4.3. Livestock and aquatic systems

The effect of the MP is not only on terrestrial food sources — the potential implications on livestock and aquatic ecosystems are enormous (Okeke et al., 2022). MPs in soil, water, and feed have the potential to be ingested by livestock, which leads to bioaccumulation in meat, dairy, and other foodstuffs. MPs could be absorbed directly through grazing or secondarily through water by livestock feeding on MP-contaminated pastures. MPs have been detected in the gastrointestinal tracts of ruminants, which indicates the bioaccumulation of MPs in the gastrointestinal organ system (Corte Pause et al., 2024). While research on livestock bioaccumulation of MPs is still in its initial stages, current data indicate that livestock well-being is affected with MP being associated with inflammation, oxidative stress, and alteration of gut microbiota (Huang et al., 2021). Moreover, MPs in livestock feed could be transferred to milk, egg, and meat products, and concerns have been raised on the potential intake of MPs through foodstuffs of animal origin (Lackner & Branka, 2024).

Aquatic ecosystems are very susceptible to MP contamination by agricultural runoff. Surface runoff and leaching transport MPs from plastic mulches, biosolids, and agrochemical packs into rivers, lakes, and groundwater (Lwanga et al., 2022). MPs, when in the aquatic environment, get ingested by fish, shellfish, and other aquatic organisms, which bioaccumulate in the various trophic levels. Relevant literature has reported the presence of MPs in commercial seafood, suggesting a potential risk of mud crabs and shellfish human exposure (Hossain et al., 2023). MPs in aquatic ecosystems may also interact with other environmental pollutants, i.e., heavy metals and persistent organic pollutants, to enhance their potential to be toxic. MP has been reported to biomagnify in higher trophic-level organisms since they consume prey containing MPs, thus having higher concentrations of MPs in predator organisms (Miller et al., 2020). The occurrence of MPs throughout freshwater and marine food webs emphasizes the need for source control on MP pollution sources to safeguard aquatic biodiversity and food safety.

5. Human health concerns

MPs are increasingly prevalent in agricultural systems and pose serious concerns for human health. As MPs can enter the food chain through all pathways: plant uptake (up to 13% of the plant mass) and hence animal consumption and contaminated water, they have toxicological risks for consumers (Pironti et al., 2021). Data on human exposure to MPs via food is still developing, however, current data indicates significant implications from chronic ingestion of MPs and contaminants that may attach to MPs. Because of the negative impacts of MP bioaccumulation and biomagnification, the global exposure of humans to MPs is a growing concern.

5.1. Toxicological impacts

MPs are gaining a lot of attention for the food ingestion route of entry into the human body through contaminated crops, seafood, and animal-derived products (Lackner & Branka, 2024). Human exposure to MPs is widespread, with MPs found in a range of food items, including fruits, vegetables, honey, salt, fish, and dairy products. Small MPs have the potential to cause physiological harm depending on size, shape, and chemistry when ingested. Smaller MPs, especially nanoplastics, are of particular concern since they have the potential to penetrate biological membranes and bioaccumulate in tissues in the human body (Yee et al., 2021). MPs have been reported to trigger cytotoxicity, oxidative stress, and inflammation in mammalian cell lines in vitro. MPs in the gastrointestinal system have the potential to disrupt the gut microbiome, impairing nutrient uptake and immune function. MPs have been reported to trigger mechanical irritation to intestinal walls with a potential link to gastrointestinal disorders (Jia et al., 2023).

Carriers of toxic substances are of high toxicological significance associated with MPs. MPs have the potential to absorb heavy metals, persistent organic pollutants (POPs), and endocrine-disrupting chemicals in the environment (Alijagic et al., 2024). When absorbed by the human body, the contaminants have the potential to be released and trigger toxicity. Certain plastic additives, i.e., bisphenol A (BPA) and phthalates, have been associated with endocrine disruption, reproductive toxicity, and an enhanced risk of metabolic disorders (Campanale et al., 2020). Little is known about the chronic effects on the health of MP with ongoing low-level exposure, and this remains an area of research.

5.2. Cumulative effects in the food chain

Of particular concern is the potential for bioaccumulation and biomagnification of MPs through food webs. Biomagnification occurs when organisms retain MPs over time and the persistent concentration of MPs within organisms also occurs over time (Miller et al., 2020). The increase of the MP levels through the food web is called biomagnification. These processes could magnify human exposure to MPs, especially for consumers of such high levels of seafood or animal products. Marine and freshwater organisms such as fish, mollusks, and crustaceans have been shown to consume and accumulate MPs in their digestive tracts and other tissues (D'Costa, 2022). As humans consume these organisms, MPs accompanied by their associated contaminates can be bio-transferred to consumers. Likewise, MPs consumed by livestock via contaminated feed and water can find their way into meat, milk, and eggs. The degree to which MPs are absorbed into the bloodstream or other organs after they have been ingested remains under investigation; however, preliminary data suggest a potential risk for systemic toxicity. In addition to direct ingestion, MPs present in food packaging materials can underlie human exposure to MPs. Plastic packaging may also shed MPs into food products (Canga et al., 2024), especially at high temperatures or through very long storage durations. It pointed to the need for better regulation and for alternative packaging materials to mitigate the risks of MP contamination.

6. Potential approaches and methods to microplastics abatement

The emerging evidence of health and environmental hazards posed by MPs requires more effective mitigation strategies. Given the dominant contribution of agricultural practices to MP pollution, strategies and technologies to limit MP release and accumulation in agroecosystems need to be developed (Okeke et al., 2022). A sustainable solution to this issue involves regulatory interventions, innovations in farming practices, and better monitoring strategies. Implementing sustainable alternatives and stricter controls can help minimize the presence and the effects of MPs on soil health, food safety, and the environment overall.

6.1. Regulatory frameworks and mitigation strategies

Today there are very few regulatory efforts to address MP pollution in agriculture and existing frameworks largely target provisions related to plastic waste management, and not on agricultural sources (Deme et al., 2022). The European Union (EU) has been at the forefront of active measures, adopting bans on specific plastic materials (especially single-use) and supporting research on sustainable alternatives (Munhoz et al., 2022). The United States and Canada have enacted regulations restricting the use of microbeads in personal care products; however, similar policies targeting MPs in agricultural practices are still early in development. International agreements, starting with the Basel Convention, have identified plastic pollution as a key global challenge, but their implementation in agricultural contexts is lacking (Bank et al., 2021). A significant challenge in the design of effective MP-related policies is that standardized methods for monitoring and quantifying MPs in soil and crops are lacking. Existing biosolid application regulations, for instance, target predominantly heavy metals and organic pollutants, frequently disregarding MP pollution

(Ziajahromi et al., 2024). This will strengthen policies to treat MPs as granulometrically regulated pollutants, to curb their growth in agroecosystems. These steps will help mitigate environmental exposure and reduce MP contamination in agriculture through the removal of synthetic textiles, the introduction of alternative materials, and improved management practices (Okeke et al., 2022). An option that has shown the greatest promise is the design and extraction of biodegradable mulches to replace typical plastic films. Research has shown that natural polymer-based mulches (e.g. starch or polylactic acid) can be degraded more efficiently in soil and are thus less likely to contribute MP over the long term (Zantis et al., 2024). Emerging filtration technologies, membrane bioreactors, or electrocoagulation, have been proven to decrease the MP load within the treated sewage sludge to be applied onto agricultural fields. These techniques have limitations and require additional data to refine and make them economically feasible for large-scale use (Z. Zhang & Chen, 2020). Altering irrigation practices also provides possible approaches for mitigation. Preventing MPs from entering irrigation networks can take place by utilizing cleaner water sources and fitting sewage treatment plants with better filtration systems. Moreover, the use of best management practices to minimize agricultural runoff can help reduce the translocation of MPs from agricultural parcels to aquatic systems. Moreover, addressing MP contamination in agriculture requires a multi-pronged approach involving future regulatory action, technological development, and collaboration with stakeholders (Campanale et al., 2020). The inclusion of MPs in environmental quality standards is a much-needed first step that requires strengthening legislation. Research programs to promote sustainable alternatives to plastic-based agricultural inputs should be funded. MP-reducing practices to be incentivized and awareness campaigns to be launched for farmers.

7. Current gaps in research

However, research gaps regarding MP pollution in agroecosystems persist. The potential effects of MPs, due to their interaction with soil, crops, and the food web, make the evaluation of their effects on the environment and human health particularly challenging. These gaps need to be filled to devise mitigation strategies and inform policy decisions.

7.1. Limited understanding of microplastics long-term effects on soil and plants

The long-term effects of MP accumulation in agricultural soils are still poorly characterized. MPs can change soil physicochemical properties such as porosity, water retention, and nutrient availability but the extent to which these affect soil health and productivity remains uncertain (F. Wang et al., 2022). Additionally, MPs could be ingested, which may have an adverse effect on these vital microbial communities responsible for nutrient cycling and plant growth. Preliminary studies suggest that MPs may carry pathogens or function as vectors for heavy metals and organic pollutants, but more work is needed to assess the ecological ramifications of these associations at long-term scales (Tumwesigye et al., 2023). Similarly, the ability of MPs to interfere with the physiological processes of plants needs further investigation. Long-term exposure studies are needed to determine if chronic MP contamination impacts crop yields or food safety.

7.2. Lack of standardized methods for microplastic detection in agricultural matrices

The lack of validated analytical methods for detecting MPs in soils, water, and plants has been a main roadblock to the progression of MP assessment in agriculture. The situation is much different for terrestrial environments as plans for MP monitoring in complex terrestrial matrices are inconsistent compared to aquatic environments where advances have been made. Differences in the sample preparation, extraction, and characterization techniques result in discrepancies in reported MP concentrations and characteristics (Fu et al., 2020). It is important to establish standardized procedures for MP identification and quantification to facilitate comparability between studies. Several advanced methods, including Raman spectroscopy and gas pyrolysis-chromatography-mass spectrometry (Py-GC-MS), have demonstrated potential for MP analysis but need adaptation for use in studies involving MPs in agriculture. With consistent global standards data will be more reliable and regulatory oversight easier (Q. Zhou et al., 2023).

7.3. Insufficient studies on the bioavailability of microplastic in the food chain

Although contamination of crops, livestock feed, and irrigation water with MPs has been reported, the degree to which MPs are bioavailable and accumulate in organisms throughout the food web has not been sufficiently examined. Studies on aquatic ecosystems have suggested that MPs can trophically transfer, but whether comparable processes occur within terrestrial food webs remains uncertain (Carbery et al., 2018). The behavior of MPs and their associated chemical additives within agricultural food chains is essential for evaluating human health risk potential.

8. *Quo Vadis*? future directions

In consideration of the existing knowledge bases on food systems and their associated research gaps, we recommend that such efforts should be aimed toward interdisciplinary research between soil science, plant physiology, toxicology, and food safety. Overcoming these uncertainties will necessitate a blend of empirical fieldwork, laboratory experiments, and state-of-the-art modeling approaches. Developments in MP mitigation techniques will be slower and require policy-making based on targeted research. These patterns were not uniform across the field, indicating that MP accumulation may vary in different agroecosystems; therefore, governments and environmental agencies need to invest in large-scale field studies assessing MP accumulation trends in different agroecosystems (Okeke et al., 2022). Besides, the government should also try to update the usage of plastic-based agricultural inputs and help supply biodegradable alternatives as well as improve waste management to limit plastic loss to the environment. Smart agricultural practices need to be reconsidered to ensure they are suited to the new threats posed by MP pollution (Milojevic & Cydzik-kwiatkowska, 2021). Decreasing reliance on plastic-based mulches, using organic soil additives without plastic pollution, and enhancing biosolid treatment technologies are effective ways to reduce MP influxes into agricultural fields. Besides, adopting circular economy strategies like the recycling of agricultural plastic and innovating bio-based alternatives can lead to long-term sustainability as well (Rani et al., 2024). Need more Public awareness campaigns that stress the health hazards of MPs' presence in the food chain. Educational materials tailored to farmers or the general consumer could raise awareness of potential MP sources, mitigation opportunities, or whether certain food items are less likely to contain MPs, further increasing responsible land management practices and environmentally friendly dietary choices (Qi et al., 2020).

9. Conclusion

MP contamination of agricultural systems presents an emerging environmental concern that poses serious ramifications for food safety, soil health, and the sustainability of ecosystems. The extensive application of plastic-based materials in agriculture like mulches, biosolids, irrigation systems, and agrochemical packing leads to the accumulation of MPs in the soil and water. After being introduced into agroecosystems, MPs display multiform transport and fate dynamics, persisting in soils, leaching into water bodies, and possibly integrating plants. Their presence in edible plant tissues, transactional pathways via livestock and aquatic systems, and implications for human exposure and adverse health effects—especially for bioaccumulated MPs and those with leachable toxic additives—from environmental contaminants have long-term implications. Although research on this topic is growing, there are major knowledge gaps, particularly regarding the long-term consequences of MPs for soil microbial communities, crop productivity, and trophic transfer in terrestrial food webs. The absence of systematic detection methods compounds the difficulty in accurately assessing risks and implementing appropriate regulatory measures. MP contamination persistence and effects on fresh produce will necessitate improved policies, sustainable agricultural practices, and greater public awareness to avoid—ideally, prevent—further contamination at land-fresh produce-watershed pathways in the future. These efforts should include developing biodegradable alternatives, better-managing waste plastic, and establishing strong monitoring frameworks to protect food security and environmental health. Overcoming these hurdles will take a global effort to shift to a more sustainable, plastic-aware farming industry.

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